THE ASTROPHYSICAL JOURNAL, 272:L61–L65, 1983 September 15

GAMMA-RAY OBSERVATIONAL CONSTRAINTS ON THE ORIGIN OF THE OPTICAL CONTINUUM EMISSION FROM THE WHITE-LIGHT FLARE OF 1980 JULY 1

J. M. RYAN, E. L. CHUPP, D. J. FORREST, AND S. M. MATZ
University of New Hampshire

E. RIEGER, C. REPPIN, AND G. KANBACH
Max Planck Institute for Physics and Astrophysics

AND

G. H. SHARE
E. O. Hulburt Center for Space Research, Naval Research Laboratory
Received 1983 January 18; accepted 1983 May 18

ABSTRACT

We report here the results of γ-ray observations of the white-light flare of 1980 July 1 which started at approximately 1627 UT. We conclude that the major white-light emission which occurs in the late phase of the flare could not have been due to heating by electron or ion precipitation. This conclusion is based on the fact that the X-ray and γ-ray flux as measured by the Gamma-Ray Spectrometer on the *Solar Maximum Mission* (*SMM*) satellite peaks approximately 1 minute before the maximum of the optical continuum emission. Approximately 73% of the optical continuum emission, representing a spatially and temporally distinct bright point, follows this maximum with little or no X-ray or γ-ray emission in the same period.

Subject headings: gamma rays: general—Sun: flares

I. INTRODUCTION

It has been suggested that energetic ions and electrons accelerated in solar flares produce the optical continuum observed in some flares (Schatzman 1965; Najita and Orrall 1970; Svestka 1970). A coincidence in time of the optical continuum emission with either or both the bremsstrahlung radiation from electrons or prompt nuclear line radiation from ions is required to support this thesis. Prompt nuclear γ-ray line radiation traces the particle interaction rate of accelerated ions in the same manner as bremsstrahlung radiation traces the interaction rate of energetic electrons (Forrest *et al.* 1981). The energy range of 4.1–6.4 MeV covers several prompt CNO nuclear lines. Delayed monoenergetic lines such as the 2.223 MeV neutron capture line and the 0.511 MeV annihilation line are not useful for determining the time behavior of energetic ions because the time behavior of these lines is dependent on nuclear decay, particle transport, and capture.

Two documented observations exist of white-light flares with γ-ray measurements. These are the flares of 1972 August 7 (Chupp *et al.* 1973; Chupp 1976) and 1978 July 11 (Hudson *et al.* 1980). Although white-light observations have been reported for the flare of 1978 July 11 (Dezsö *et al.* 1980), no quantitative optical data have been reported for the impulsive phase. On the other hand, γ-ray data only exist for the decay phase of the white-light flare on 1972 August 7. In this *Letter* we present results for the flare of 1980 July 1 starting at approximately 1627 UT, in which simultaneous measurements were made of X-ray, γ-ray, and optical continuum emission for the entire duration of the flare. This is the first occurrence of a comprehensive, coincident set of observations.

The γ-ray and X-ray observations were made by the Gamma-Ray Spectrometer (GRS) on the *Solar Maximum Mission* (*SMM*) satellite. The GRS is composed of an array of seven gain-stabilized 3″ × 3″ NaI detectors operating in the range from 0.3 to 9 MeV and two X-ray monitors covering the range from 10 to 140 keV. A complete description of the instrument can be found in Forrest *et al.* (1980). The optical measurements were made at the Sacramento Peak Observatory and the Big Bear Solar Observatory (Zirin and Neidig 1981).

In the following section we present the X-ray and γ-ray data and briefly review the optical measurements performed and discussed by Zirin and Neidig (1981). In the discussion section we summarize the evidence for the case against general particle-produced white light.

II. OBSERVATIONS

We present in Figure 1 the impulsive phase count rates (time resolution 2 s) observed in three energy

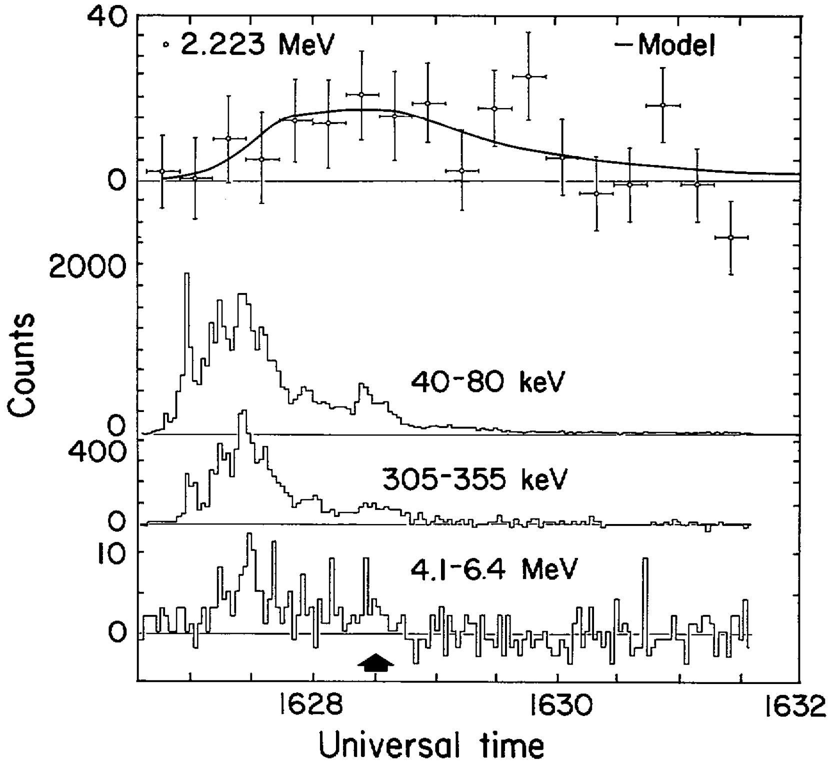

FIG. 1.—The time history of count rates in four energy channels, 40–80 keV, 305–355 keV, 4.1–6.4 MeV, and the deuterium formation line at 2.223 MeV. The highest energy band contains the emissions of prompt nuclear lines indicative of nucleonic interactions, while the X-ray energy band counts are primarily due to energetic electron bremsstrahlung. Superposed on the deuterium formation line data is the best model for the intensity of this line, assuming the neutron production is traced by the nuclear line window count rate and assuming an exponential decay of the neutron population. Indicated on the time axis is the point after which 73% of the optical continuum luminosity follows.

bands; the hard X-ray region at 40–80 keV, 305–355 keV, and the γ-ray region at 4.1–6.4 MeV. Although 2.2 MeV line emission establishes the presence of energetic ions in this flare, no resolvable, statistically significant, prompt nuclear lines were detected in the 4.1–6.4 MeV range. The ratio of the total counts in the 2.2 MeV line to the total counts in the 4.1–6.4 MeV range is consistent with that measured in many other flares (Chupp 1981). In addition, the time-integrated solar flux in the 4.1–6.4 MeV range for the 1980 July 1 flare is well above the extrapolated power-law continuum $dN/dE = AE^{-\alpha}$ cm^{-2} MeV^{-1} ($A = 15.0, \alpha = 2.8$) which was fitted to data below 1 MeV. This strongly suggests that this flare was similar to other γ-ray flares in that γ-ray line emission due to energetic ions was present (Forrest *et al.* 1981). The rates in these three energy bands in Figure 1 exhibit similar temporal structures, with rise and fall times of the emission as short as $\sim$ 4 s.

Also plotted for comparison is the time profile of the 2.223 MeV formation line of deuterium. This line was detected at the 5.3 σ level following the impulsive phase of the flare with an integrated intensity of 3.2 ± 0.6 photons cm^{-2}. This line is formed when the neutrons produced during the impulsive phase are captured on hydrogen in the photosphere. As noted earlier, the temporal behavior of this line does not directly determine the time behavior of the energetic protons or ions which could in principle produce white light (see Kanbach *et al.* 1981; Wang and Ramaty 1974). However, as in other γ-ray flares, these data are consistent with all the neutron production occurring during the impulsive phase of the flare, in this case before 1628:30 UT (Chupp *et al.* 1981). If we assume that neutron production is traced by the count rate in the nuclear line window at 4.1–6.4 MeV, then we obtain a 75^{+75}_{-25} s decay time for the deuterium formation line, consistent with a previous observation (Chupp *et al.* 1981).

Shown in Figure 2 are the measurements of the optical continuum made at the Sacramento Peak and Big Bear Solar Observatories (Zirin and Neidig 1981). Three bright points (labeled A, B, and D by Zirin and Neidig 1981) were observed during the impulsive phase of the flare. Their intensity diminished significantly by 1628:30 UT (see arrow in figures). The most intense, largest, and longest lived bright point (labeled C) became visible at 1628:30 UT. The three early points A, B,

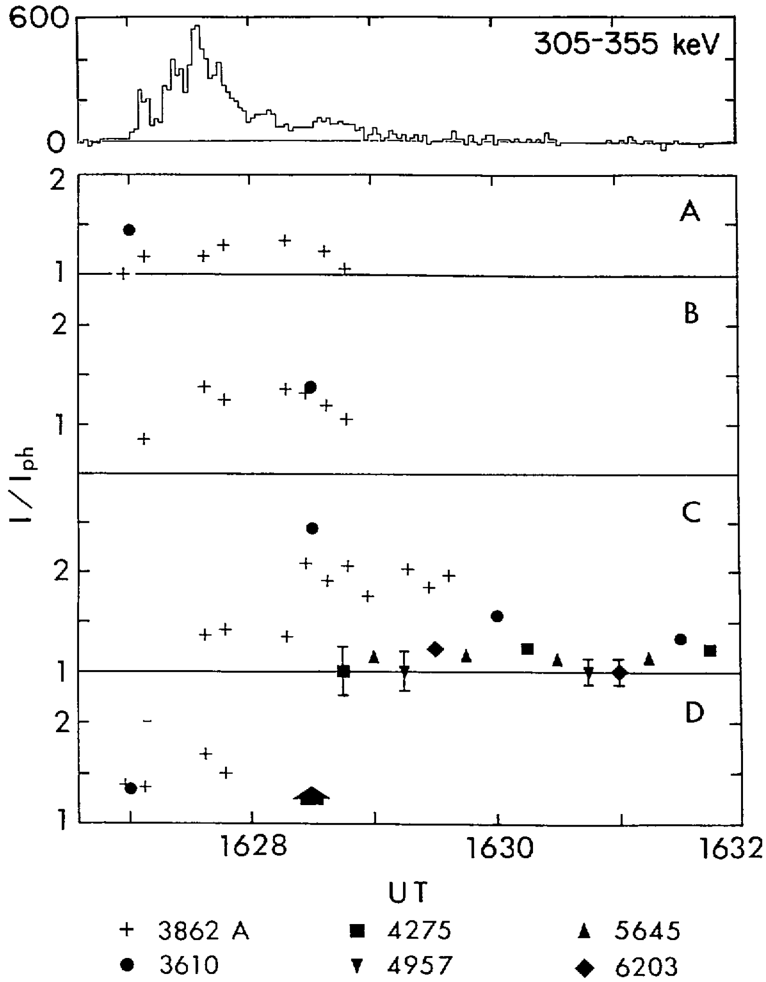

FIG. 2.—Intensity light curves of white-light kernels. Multiplying by the appropriate area and bandwidth factors indicates that 73% of the emission occurs after 1628:30 UT (*arrow*) primarily in point C (Neidig 1982). (From Zirin and Neidig 1981; used by permission). The 305–355 keV γ-ray count rate profile is included for reference.

and D were also physically displaced from the dominant point C. Densitometer measurements by Neidig (1982) indicate that most (~ 73%) of the optical continuum emission occurred after 1628:30 UT in the large point C and that its luminosity integrated over time and area was approximately 1.8×10^{30} ergs. In contrast, approximately 97% of the hard X-ray and nuclear γ-ray emission occurred before 1628:30 UT.

III. DISCUSSION

The impulsive hard X-ray and prompt γ-ray emissions from the 1980 July 1 flare are similar and primarily concentrated in an approximately 90 s interval from 1627:00 UT to 1628:30 UT with maxima around 1627:30 UT. The maximum in the optical continuum emission occurred about 60 s later at 1628:30 UT (Zirin and Neidig 1981). Only about 27% of the white-light emission as measured in the bright points A, B, and D occurred during the same time interval as all the prompt X-rays and γ-rays. The poor temporal correlation of the prompt X-rays and γ-rays with the bulk of the white-light emission representing the entire luminosity of point C is compelling evidence against the energetic particle origin of white-light emission as originally proposed by Schatzman (1965).

The energetic particle origin of the post-impulsive phase continuum emission from point C can be ruled out on other grounds. The energy content of the total point C emission is between a factor of 18 and 36 more than we estimate for that contained in the energetic ion population (see below). In addition, if energetic particles created during the impulsive phase produce the optical emission at such a late time, they must be stored in a low-density region for approximately 1 minute and then precipitate in denser regions without the emission of any X-rays or γ-rays. We can also rule out, for several reasons, the suggestion made by Zirin and Neidig (1981) that the optical continuum emission is related in some way to the secondary deuterium formation line. We first note that there exists a high value of the deuterium formation line (2.223 MeV) at 1629:45 UT; however, it represents only about 15% of the total emission in this line. Second, there is no measurable accompanying emission at higher energies as would be caused by appreciable numbers of precipitating protons or ions above 10 MeV. Third, the total energy in the neutrons producing the 2.223 MeV line falls four orders of magnitude below the required energy in the white light. Finally, proton precipitation obeying the time profile of the kernel C emission, would produce an intense and prolonged emission at 2.223 MeV rather than a short, weak burst over 1 minute after the time of peak precipitation. We thus attribute the high value at 1629:45 UT to a statistical fluctuation. We can find no plausible or reasonable mechanism by which energetic protons or ions produce any of the optical continuum emission after 1628:30 UT.

Bright points A, B, and D occurred about 1 minute before point C during the impulsive X-ray and γ-ray emission prior to 1628:30 UT, and it is possible that these early bright points were produced by energetic particle precipitation, while point C requires some other origin. Zirin and Neidig (1981) report that points A and B were more compact and variable than point D, and thus they may be more likely candidates for particle heating origin. The total optical luminosity in kernels A, B, and D is approximately 6×10^{29} ergs (Neidig 1982). We can compare this with the inferred energy of the ion beam derived from the γ-ray measurements. Assuming that the accelerated ions follow a power-law spectrum in energy and are incident on a thick target (chromosphere or upper photosphere), then using the observed ratio of prompt 4.43 MeV to delayed 2.223 MeV γ-rays (0.1 ± 0.09), we derive a best fit power-law spectrum with an index of -4.0 ± 0.5 (see Ramaty, Kozlovsky, and Lingenfelter 1975). Normalizing to the observed γ-ray fluence, we thus find that the accelerated ion beam contains about 10^{29} ergs of energy in the form of particles greater than 1 MeV. This is similar to another energy estimate for this flare of 5×10^{28} ergs (Ramaty 1982). Although the energy content estimate of optical continuum emission exceeds that of the ions, the uncertainties in the densitometer calibration and the proton spectral shape do not allow us to definitively exclude the possibility that protons or ions could have the necessary energy to give rise to impulsive phase white-light kernels A, B, and D.

If we presume that white-light kernels A, B, and D were produced by energetic electron or ion heating, we consider the possibility that this optical continuum emission was from the photosphere. Lin and Hudson (1976) and Hudson and Dwivedi (1982) have shown that most of the energy from precipitating protons and electrons with power-law spectra is deposited in the chromosphere since protons below 50 MeV and electrons below 4 MeV cannot penetrate deeper than 10^{24} cm^{-2} ($\tau_{5000} = 0.04$) (Gingerich *et al.* 1971). The observed electron bremsstrahlung power-law spectrum implies a similarly shaped electron spectrum which would deposit its energy no deeper than the chromosphere, and any proton or ion spectrum with the necessary number of energetic particles to heat the photosphere to a level commensurate with these optical continuum measurements would produce at least 10^4 times as many nuclear γ-rays as observed here. Thus, the measured electron bremsstrahlung and nuclear γ-ray measurements are entirely inconsistent with particle-produced, *photospheric* optical continuum emission.

IV. CONCLUSION

Both energy and time-coincidence arguments show that most (~ 73%) of the observed white-light emission as contained in the late phase and bright point C of the 1980 July 1 flare could not have been produced by energetic particles. Based on the same arguments, it is possible that energetic particles could have produced the white light associated with the early bright points A, B, and D but not in the photosphere. However, since particles are excluded as a cause of most (and probably all) of the observed white light in this event, there is no evidence (other than time coincidence) that nonthermal particles are a cause for any of the optical continuum emission. It is now proper to consider that there is in general no causal relationship between particles and white light and that some physical process, other than nonthermal particles, is responsible for the phenomenon.

The authors wish to thank Mary M. Chupp for editing and Robert S. Hoffman for typing this manuscript. This work was partially supported by contract NAS 5-23761 at the University of New Hampshire, NASA contract S.70926A at the Naval Research Laboratory, and contract 010K017-ZA/WS/WRK at the Max Planck Institute, Federal Republic of Germany.

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E. L. Chupp, D. J. Forrest, S. M. Matz, and J. M. Ryan: Department of Physics, University of New Hampshire, Durham, NH 03824

G. Kanbach, C. Reppin, and E. Rieger: Max-Planck-Institut fur Physik und Astrophysik, Karl-Schwarzschild-Str. 1, D-8046 Garching, West Germany

G. H. Share: E. O. Hulburt Center for Space Research, Naval Research Laboratory, Code 4152, Washington, D.C. 20375